HORN ANTENNA LENS FOR MULTI-BEAM APPLICATIONS

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ABSTRACT

A spherical discrete lens antenna based on the back-to-back combination of two choked-horn antennae arrays interconnected through smooth waveguides sections implementing the spherical phasing law, has been designed, simulated and fabricated.
The spherical phasing law of the lens converts the incoming spherical phase front, from a small feeder placed at the focal plane, into a plane phase front. Depending on the feeder position at the focal plane (the perpendicular plane to the len's axis containing the focal point) the beam is pointed in different directions. The minimum angular distance between two beams is directly related to the minimum distance between two adjacent positions of low directive and, therefore, small feeders.
The selected implementation offers several advantages compared to an actually curved lens, such as the simplification of the fabrication, the constant length of the phasing waveguides and the dispersion of the back-scattered power, reducing significantly the coupling between feeders.

1. INTRODUCTION

The capability of having many different beams illuminating the earth surface from a geostationary satellite has been an issue of interest during the last few years.
The need of increasing the services provided by satellites urges the designers to propose different alternatives. The classical and conventional solution of using direct radiating arrays (DRA) is strongly limited by the maximum number of beams, since each one needs its own beam-forming network and the final number of phase-shifters and/or amplifiers increases exponentially with the number of beams. Other possibility would be to introduce some kind of lens or reflector system in order to focus certain number of beams, but there are strong limitations in the number of distortion-free beams and the maximum angular resolution that can be achieved.
In this paper a planar lens based on horn antennas is proposed, Fig.1, to generate multiple spot beams over the Earth's surface.

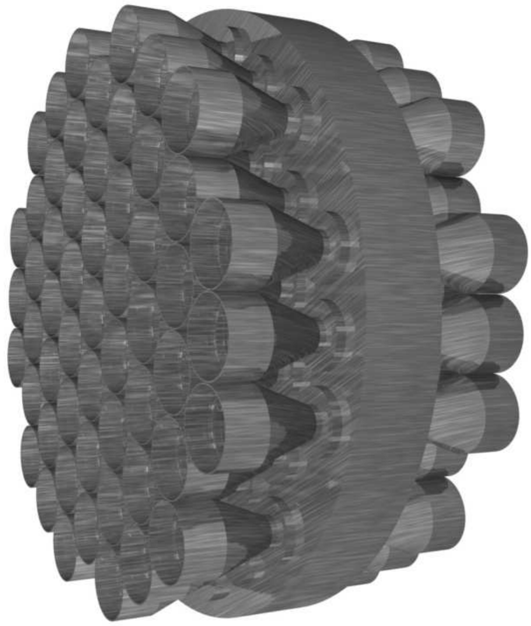

Figure 1. Discrete lens.

2. WORKING PRINCIPLE

The proposed system is inspired by the Bootlace lens concept, Fig.2. As it is well known, it is characterized by a set of receivers and transmitters interconnected through equal-length transmission lines.

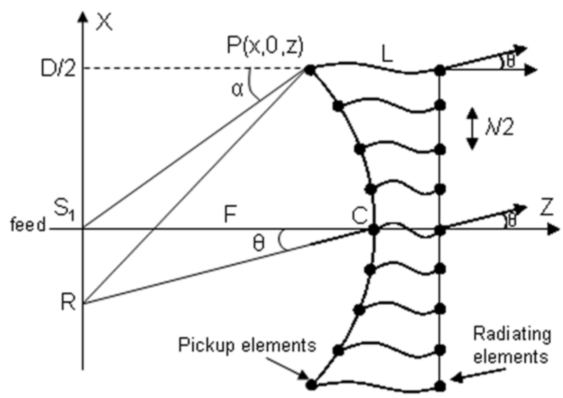

Figure.2. Bootlace Lens working principle.

Theoretically, once defined the positions of the receivers and transmitters, a movement of the feeder along the X axis generates certain scan, θ.
Since one of the system's requirements is to obtain the maximum gain possible, the transmitters will be located over a plane perpendicular to the lens' axis. Once this condition is fixed, the receivers' layout should be such that all the incoming waves from the central feeder, S_1, arrive in phase to all of them. Assuming a low directive element as a feeder, generating spherical waves, the receivers should be placed over a spherical surface with its center at the S_1 feeder position, which will become the focus of the lens.
In this case, we are interested in the properties of the canonical spherical lens and, in particular, on the capability to scan the beam just by moving the feeder position.
So, assuming that the receivers are located at points $P=(x_i,z_i)$ over a spherical surface centered at S_1, the path difference at the receiver positions between the beam generated at the focal point $S_1=(0,0)$ and a beam generated at point $R=(x_D,0)$, can be determined as follows,

$$\overline{S_1P} - \overline{RP} = F - \sqrt{(x_i + x_D)^2 + z_i^2} \,. \qquad (1)$$

being, F the focal distance (i.e. the radius of the sphere where the receivers are placed). Knowing that the receivers' position coordinates obey $x_i^2+y_i^2=F^2$, equation (1) can be rewritten as a function of x_i,

$$\begin{aligned}\overline{S_1P} - \overline{RP} &= F - \sqrt{(x_i + x_D)^2 + F^2 - x_i^2} = \\ &= F - \sqrt{x_D^2 + F^2 + 2 \cdot x_D \cdot x_i}\end{aligned} \qquad (2)$$

The square root can be expanded into a series of exponential terms as follows,

$$\begin{aligned}&\sqrt{x_D^2 + F^2 + 2 \cdot x_D \cdot x_i} = \sqrt{x_D^2 + F^2} \cdot \\ &\cdot \left[1 + \frac{x_D}{x_D^2 + F^2} \cdot x_i - \frac{x_D^2}{2 \cdot \left(x_D^2 + F^2\right)^2} \cdot x_i^2 + \ldots\right]\end{aligned} \qquad (3)$$

The binomial series is defined as a particular summation of exponential terms. The term which characterizes the series has as denominator the hypotenuse of a right triangle of sides x_D and F. x_D is also the numerator and it is small compared with F, thus, the relevance of the terms decreases as their exponent increase. As a result, it is possible to neglect the higher order terms, keeping the first two describing, with a small error, the path difference as a linear function along X axis,

$$\overline{S_1P} - \overline{RP} \approx F - \sqrt{x_D^2 + F^2}\left[1 + \frac{x_D}{x_D^2 + F^2} \cdot x_i\right] \qquad (4)$$

The smaller x_D is compared to F, the better the approximation will be.
From the radiation point of view, this progressive increment, or decrement, of the path difference along X axis is translated into an effective scan of the radiated beam.

3. IMPLEMENTATION PLANAR LENS

3.1. Preliminary geometrical considerations

In this case, a demonstrative prototype for a multi-beam transmit antenna in Ka band for a geostationary satellite will be defined. The frequency is fixed to 20 GHz and choked-horn antennas will be used as lens elements. In principle, the scanning capabilities of the lens system should distribute the maximum number of beams inside a tri-dimensional cone of 10 degrees.
Additionally, since some amplification will be required at the satellite, it can be conveniently placed inside the lens in the connecting waveguides between receivers and transmitters.
The straight implementation of the lens would force us to distribute the transmitters over the radiating plane, the receivers over a curved surface and interconnecting them through equal-length flexible transmission waveguide sections. The curved surface where the receivers are to be placed and the interconnections are not easy to implement, being a strong drawback of this approach.
However, it is possible to reconsider some of the design principles, for instance, the most restrictive one: the need of having equal-length transmission lines between receivers and transmitters. It is possible to move the receivers towards the transmitters, placing them also in a flat (not spherical) fashion and then compensate the introduced phase-shift with the interconnecting waveguides so the desired phase front is preserved. This phasing also follows the same spherical law, so we keep the scanning properties of the spherical lens but with a planar implementation. The disadvantage is that now the phasing is not equal for all the elements and it is dependent on its relative position inside the lens. However, from the fabrication point of view, despite this different phasing, the fabrication procedure is much simpler.
The required phase corrections correspond to the path difference between the Focal point and the position of each one of the receivers. The formula is very simple:

$$d_i = \overline{S_1P_i} = \sqrt{x_i^2 + z_i^2} = \sqrt{x_i^2 + F^2} \,, \qquad (5)$$

being d_i the distance from the focal point $S_1=(0,0)$ to the point $P_i=(x_i,z_i)$, and $z_i=F$, since all the receivers are in a plane perpendicular to the lens axis, i. e., $z=constant$.

It is important to note that despite the change introduced in the design, the spherical law is maintained and therefore, the scanning capabilities.

3.2. Phase-shifters implementation

In order to introduce the phasing in a very simple way, equal-length circular waveguide sections of different inner radius are used. The different inner radius generate different transmission constants and therefore, different phasing when passing through them.

The input radius of the horn antennas used is 5 mm, so the waveguide sections will change, slightly, this value to get the desired phasing in transmission.

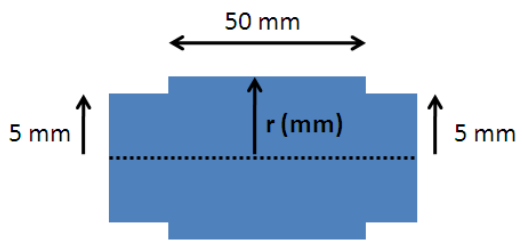

Figure 3. Phase-shifters geometry

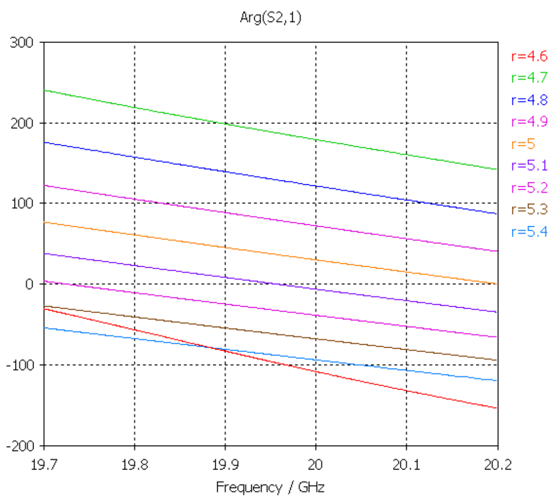

Figure 4. Transmission phase vs frequency for different values of inner radius.

There is a logical limitation in the possible values to be used for this variation. As the radius decreases we get closer to the cut-off frequency thus generating higher reflection. On the other hand, as the value increases, higher order modes could propagate and the insertion losses would also increase.

As it can be observed in Fig.4, the phase responses are quite parallel to each other, so good performance is expected within the depicted bandwidth, which is the bandwidth of interest.

3.3. Horn antenna design

The horn antenna design used for the prototype is a choked horn antenna, Fig. 5, having an aperture of *46 mm* and an approximated length of *73 mm*. The far field pattern is quite acceptable, Fig. 6; the symmetry of the obtained beam is quite high, the cross-polarization is really low and the aperture efficiently is also high.

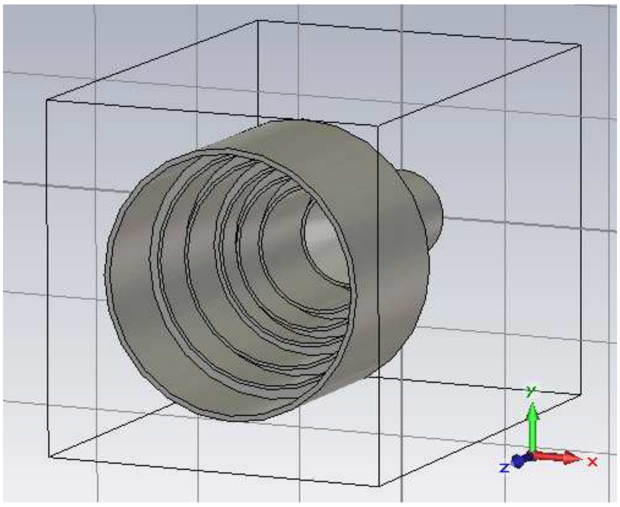

Figure 5. Tri-dimensional representation of the designed horn antennas.

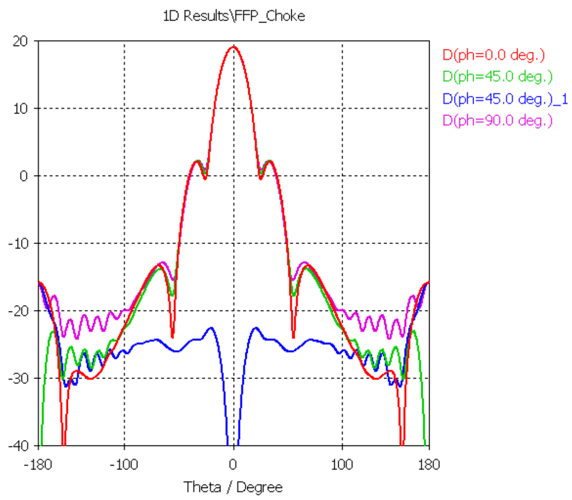

Figure 6. Choked horn antenna far field pattern. E, 45 and H planes in red, green and magenta, respectively; and the cross polarization for the 45 plane in blue.

4. SIMULATION RESULTS

The simulations were undertaken in CST Microwave Studio® software proving that the scanning capability predictions agreed with the simulation results.
The lens diameter, Fig. 7, is 408 mm and the focal distance 510 mm. The waveguide sections where the phasing is implemented have a length of 50 mm. The final system is quite simple and robust.

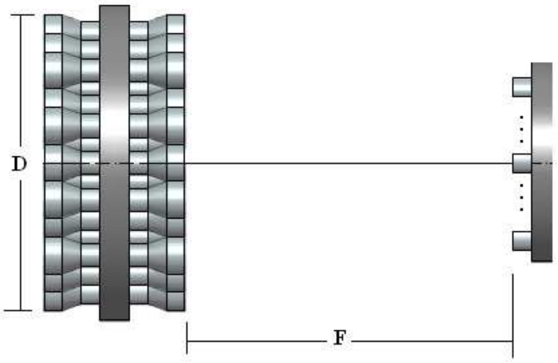

Figure 7. Artist impression of the discrete lens and the plane of the feeders are shown.

To obtain the maximum desired scanning, for instance 10 degrees, the phase increment at the aperture plane should be approximately of 62.3 degrees per wavelength, i. e., a path difference of 0.173λ per transversal wavelength at the aperture plane. From the derived equation (4), this value exactly corresponds with the slope of the linear approximation,

$$\frac{x_D\sqrt{x_D{}^2+F^2}}{x_D{}^2+F^2}=\frac{x_D}{\sqrt{x_D{}^2+F^2}}=0.173 \quad (6).$$

Operating with the previous expression, the relation between x_D and F could be obtained:

$$\frac{x_D}{0.173}=\sqrt{x_D{}^2+F^2}; \quad x_D=\frac{F}{5.6693} \quad (7).$$

Proceeding in a similar way, the required displacements x_D (related to the focal distance, F) of the feeders for other scan angles could be obtained, and they are shown in Table I.
Four different situations were simulated. The first one with a centered feeder, figure 8, and off-centered feeder moved 30, 60 and 90 mm up, which generated a beam scanning of about 3.3, 6.6 and 10 degrees down, figure 10.

Scan (º)	Slope (º/λ)	Relation x_D/F
10	62,513344	0,17632698
9	56,316407	0,15838444
8	50,102316	0,14054083
7	43,872964	0,12278456
6	37,630247	0,10510424
5	31,376067	0,08748866
4	25,112331	0,06992681
3	18,840944	0,05240778
2	12,563819	0,03492077
1	6,2828663	0,01745506
0	0	0

Table I.- Required slope and R/F relation to generate a certain scan angle.

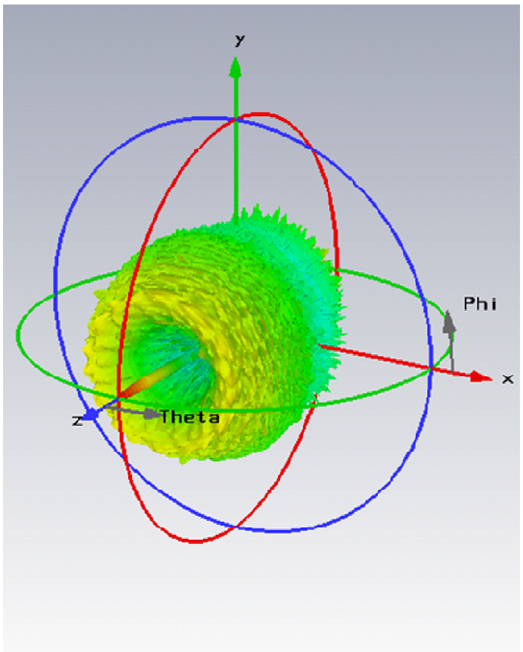

Figure 8. Far field pattern of the centered feeder.

It is important to take into account that the subtended angle from the central feeder is defining a tridimensional cone of 20 degrees.
It can be observed that for the angles greater than 20 degrees, approximately, the power is radiated directly by the feeder, since it does not intercept the lens.
It is also interesting to notice that the calculated gain for the whole system is 17.18 dB. Nevertheless, the generated beam is much directive, close to 38 dB, which corresponds with the expected value. This difference between gain and directivity, explained with the high spillover, would not be a problem in a real case where the amplification would be introduced inside the lens, since the relevance of this spillover would be reduced with the amplification factor.
In figure 9, the four far field patterns of the combination of the lens excited with the centered feeder and the three shifted ones, are compared with the far field pattern of the feeder (coincidence with the power

radiated away of the lens) and the far field pattern of one of the horns of the lens, which define the scan loss of the system.
It can be observed how the scanning is working properly.

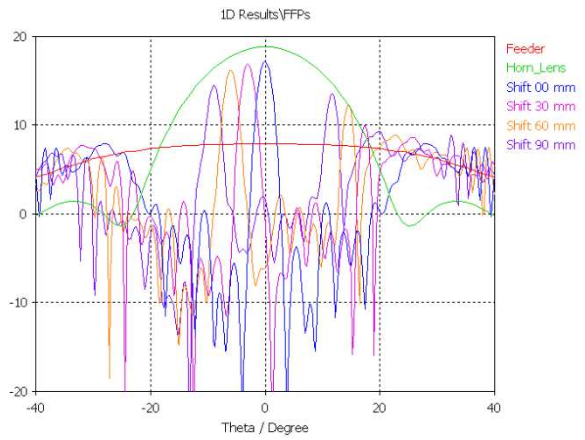

Figure 9. The far field pattern for the four cases compared with the far field pattern of the feeder and one horn of the lens.

A second problem that can be observed in the figure 9 is the appearance of grating lobes, especially for the greatest scan angles. This is clearly defined by the periodicity of the discrete lens, being the result of the tradeoff between reducing the number of horns (and therefore, number of amplifiers, phase-shifters, and so on) and maintaining the cone of interest (±10 degrees) free of grating lobes.
In our particular case, the appearance of these grating lobes shows us that the phasing has been done properly.
In the case of combining several beams simultaneously, the capability to introduce new beams is only limited by the possibility of introducing a new feeder. The ones used are 5 mm radius open-ended waveguide apertures. So, assuming a period of 12 mm in a hexagonal lattice, the number of possible feeders could be as high as 169, creating the corresponding simultaneous beams. The angular resolution will depend on the lattice, but it could be quite close to 1 degree.
The amplifiers are the same for each of the lens elements, and they should be working in a very similar regime, amplifying all the band of interest.

5. CONCLUSIONS

A discrete lens based on two horn antenna arrays connected back-to-back through equal-length waveguide sections implementing a spherical phasing law has been presented.
Probably, the system is not useful as presented since the spillover is quite important if amplification is not included inside the lens. However, it is a quite robust implementation of a planar spherical lens, and useful for multiple-beam applications from a geostationary satellite.

6. ACKOWNLEDGEMENTS

The authors would like to thank to the Space section of EADS CASA S.A., in particular to Antonio Montesano, Ana Olea and Jennifer Campuzano, for the interesting discussions and suggestions provided.

7. REFERENCES

[1] E. Brookner (ed), "Practical Phased Array Antenna Systems", Artech House, 1991.
[2] C.A. Balanis, "Antenna Theory Analysis and Design ", *Third edition, Willey, 2005*.
[3] R.J. Mailloux, "Phased Array Antenna Hand Book", *Artech House, 1994.*
[4] W. Rotman, R. Turner, "Wide-angle microwave lens for line source applications", *IEEE Transactions on Antennas and Propagation*, Volume: 11, Issue: 6, 1963 , Page(s): 623 - 632

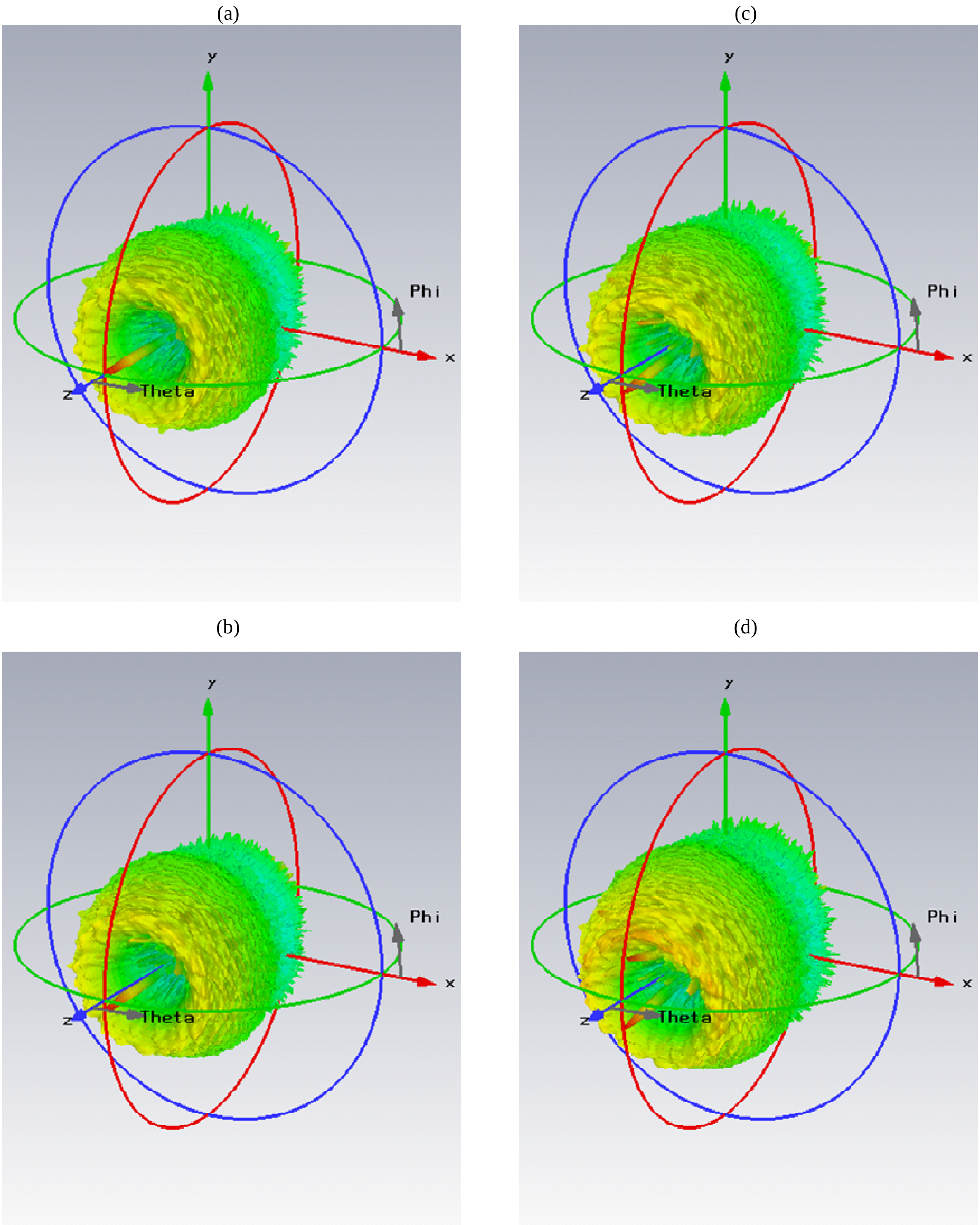

Figure 10. The tri-dimensional far field patterns of the combination of the lens and feeder for the centered feeder (a), and shifted 30 (b), 60 (c) and 90 mm (d).